Centrality dependence of strangeness production in heavy-ion collisions as a geometrical effect of core-corona superposition

F. Becattini

Università di Firenze and INFN Sezione di Firenze, Florence, Italy

J. Manninen

INFN Sezione di Firenze, Florence, Italy

It is shown that data on strange particle production as a function of centrality in Au-Au collisions at $\sqrt{s}_{NN} = 200$ GeV can be explained with a superposition of emission from a hadron gas at full chemical equilibrium (core) and from nucleon-nucleon collisions at the boundary (corona) of the overlapping region of the two colliding nuclei. This model nicely accounts for the enhancement of ϕ meson and strange particle production as a function of centrality observed in relativistic heavy ion collisions at that energy. The enhancement is mainly a geometrical effect, that is the increasing weight of the core with respect to corona for higher centrality, while strangeness canonical suppression in the core seems to play a role only in very peripheral collisions. This model, if confirmed at lower energy, would settle the long-standing problem of strangeness under-saturation in relativistic heavy ion collisions, parametrized by γ_S. Furthermore, it would give a unique tool to locate the onset of deconfinement in nuclear collisions both as a function of energy and centrality if this is to be associated to the onset of the formation of a fully equilibrated core.

I. INTRODUCTION

One of the observed features of hadron production in relativistic heavy ion collisions is the deviation from full chemical equilibrium of particles containing strange constituent quarks. This is described by a phenomenological factor $\gamma_S^{n_s}$ (n_s being the number of strange quarks in the given hadron species) which multiplies the equilibrium abundance of hadrons and turns out to be generally < 1. Actually, γ_S shows a mild increase as a function of centre-of-mass energy for central collisions from 0.65 at $\sqrt{s}_{NN} \sim 4.5$ to about 1 at 200 GeV [1], according to most analyses [2]. However, even at the largest energy of Au-Au collisions, γ_S turns out to be less than 1 in peripheral collisions, showing a monotonically decreasing trend going from central to peripheral [1, 3, 4].

The idea that γ_S could be the effect of superposing particle production from different sources in a single heavy ion collision was put forward in refs. [5, 6]. In ref. [5, 7], the multiplicities of various hadron species in Pb-Pb collisions at SPS were described well with this core-corona picture assuming that corona is a halo of single nucleon-nucleon collisions where produced particles escape the interaction region unscathed, while the core gives rise to a completely equilibrated hadron gas, i.e. with $\gamma_S = 1$. Since strangeness production is suppressed in NN collisions with respect to a fully equilibrated hadron gas, while temperature is almost the same [7, 8]), if such single NN collisions accounts for a significant fraction of total particle production, a global fit to one hadron-resonance gas would actually find γ_S significantly less than 1. In ref. [6], the authors assume that a string percolation process gives rise to a large cluster in the core of the nuclear overlapping region and smaller clusters in the outer region (henceforth referred to as corona), eventually decaying into hadrons according to the statistical model *ansatz*. With this core-corona superposition scheme, and assuming $\gamma_S = 1$ the authors could reproduce the centrality dependence of K/π ratio at SPS and RHIC because small corona clusters suffer the so-called canonical suppression effect.

This core-corona model has been applied to other observables. It has been found to be able to describe rapidity densities of charged hadrons in Au-Au collisions [9]. More detailed analysis found out that the rapidity densities of various hadron species as a function of centrality in Au-Au collisions at $200A$ GeVat RHIC as well as nuclear modification factors are well described with the EPOS model in a core-corona scheme[10]. Finally, it has been taken into account also for analysis of J/ψ production within the statistical hadronization model [11].

In this paper, we will show that this core-corona superposition nicely accounts for strangeness enhancement as a function of centrality observed at RHIC. The key probe which demonstrates the viability of this picture is the ϕ meson, which, being a completely neutral particle, does not feel canonical suppression. This, as we will discuss in detail in Sect. III, favours the picture of corona as originated from NN collisions rather than small clusters hadronizing into a fully equilibrated hadron gas. In fact, in the statistical hadronization model, sufficiently small clusters entail canonical suppression for open strange particles, but not for those with hidden strangeness.

In ref. [7], we fitted the number of single nucleon-nucleon collisions taking place in the corona as a free parameter. In this paper, we will assume a definition of corona as those nucleons which undergo one collision and show that this succesfully accounts for the ϕ meson centrality dependence. Indications that strangeness suppression is related to the number of multiply colliding nucleons were found in ref. [4] and, very recently, in ref. [12]; in this work, we clarify this

relation.

The basic ideas and conclusions discussed here have been reported earlier in ref. [13]; in this work, we expand, explain and update our analysis.

II. STATISTICAL MODEL AND CANONICAL SUPPRESSION

Statistical model analyses [1, 3, 14] in Au-Au collisions at $200A$ GeV with mid-rapidity densities find that the chemical freeze-out temperature as well as the baryon chemical potential are constant throughout the accessible centrality range implying that the thermodynamical state of the produced matter at mid-rapidity does not depend on centrality at chemical freeze-out. Not so for the strangeness under-saturation parameter γ_S which is found to be significantly less than 1 in peripheral collisions.

It has been argued [15] that $\gamma_S < 1$ is an effect of so-called canonical suppression effect. Namely, strange particles are suppressed with respect to their expected yield in a grand-canonical ensemble (or thermodynamic limit) because strangeness is exactly vanishing within a small volume, called strangeness correlation volume (SCV), which does not coincide with the volume of the average fireball at mid-rapidity or the global freeze-out volume of fireballs. Therefore, going from pp collisions to central heavy ion collisions through peripheral ones, one should observe a relative enhancement of strange particles due to approaching the thermodynamic limit, which is hierarchical: Ω yield increases faster than Ξ which increases faster than Λ's or kaons. Yet, although this hierarchy of enhancements has been observed both at SPS [16] and RHIC [17], in neither case the natural saturation expected when SCV attains a sufficiently large value is seen. In fact, this means that the SCV would only reach its saturation value (the one sufficient for the system to be essentially grand-canonical) at RHIC precisely in central collisions, where $\gamma_S \simeq 1$. Therefore, we think that canonical suppression is quite an unnatural explanation of the data, as pointed out by many [12, 13, 18, 19].

There is, however, a clearcut probe to test the canonical suppression picture and this is ϕ meson. It is not an open strange particle, thus it is not canonically suppressed, yet, being a s$\bar{\text{s}}$ state, it must be γ_S^2 suppressed. Furthermore, ϕ meson has almost no feeding from heavier species, so it does not suffer canonical suppression even indirectly as a decay product of open strange particles. It was pointed out quite early [20] that a statistical model with canonical suppression mechanism, i.e. with SCV as additional parameter, would have not been able to explain the deviation of the ϕ meson yield from its grand-canonical value and this has been demonstrated in fits to NA49 multiplicities [5]. Recently, STAR collaboration has measured the mid-rapidity densities of ϕ meson very accurately and the observed pattern as a function of centrality clearly shows (see fig. 1) that these do not scale linearly with the number of participants, rather the ratio to pp value increases rapidly at very peripheral collisions slowly saturating thereafter. This non-linear increase cannot be accounted for by a variation of the chemical freeze-out temperature because this is constant as a function of centrality, as has been mentioned. The only way to accommodate the ϕ meson behaviour in a statistical model fit is to introduce a γ_S factor, which is found to be significantly less than 1 in peripheral collisions.

Instead of introducing an *ad hoc* parameter to describe centrality dependence of ϕ meson and other strange particle yields, we can try to explain strange phase space under-saturation as an effect superposing two different particle sources, as has been mentioned in the Introduction: a fully equilibrated core (i.e. a hadron gas with $\gamma_S = 1$) and single NN collisions in the corona. The appearance of γ_S in global statistical model fits is owing to the suppression of relative strangeness production (with respect to hadron gas in full equilibrium) in the unavoidably present single NN collisions in the corona. This picture would naturally account for the decrease of fitted γ_S in peripheral collisions, where the core is smaller and the importance of single NN collisions grows.

It should be pointed out that statistical model fits to pp collisions generally find temperatures only 10% higher than in heavy ion collisions at the same beam energy but consistently lower $\gamma_{S\,\text{pp}} \simeq 0.5$, i.e. about a factor 2 smaller [7]. This explains why, in this core-corona model, no effect is seen in global fits on centrality dependence of temperature but a significant dependence of γ_S.

Finally, the shape of normalized ϕ mid-rapidity density in fig. 1 also tells us that the corona cannot be really made of small clusters hadronizing into a fully equilibrated hadron gas at the same temperature of the core. Indeed, in this case, $\gamma_S = 1$ and one could account only for the suppression of open strange hadrons but not of ϕ.

III. CORE-CORONA SUPERPOSITION

In the following, we will introduce a very simple model which is suitable to study core-corona superposition in heavy ion collisions and, particularly, to estimate the relative weight, in terms of particle production, of core and corona as a function of centrality.

It has been observed[21, 22] that the number of charged hadrons emitted in hadron-nucleus (hA) collisions, compared with pp collisions at the same beam energy, scales as:

$$\left\langle \frac{\mathrm{d}N^{ch}}{\mathrm{d}y} \right\rangle_{\mathrm{hA}} \Big/ \left\langle \frac{\mathrm{d}N^{ch}}{\mathrm{d}y} \right\rangle_{\mathrm{pp}} = \frac{N_{\mathrm{P}}^{\mathrm{hA}}}{N_{\mathrm{P}}^{\mathrm{pp}}} = \frac{N_{\mathrm{P}}}{2} = \frac{N_{\mathrm{coll}}+1}{2}, \tag{1}$$

where N_{coll} is the number of collisions. Based on the above formula, the rapidity density of a given hadron species i in heavy ion collision at mid-rapidity is written as a sum of two contributions:

$$\begin{aligned} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle &= \frac{N_{\mathrm{PC}}}{2} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{NN}} + \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}} \\ &\simeq \frac{N_{\mathrm{PC}}}{2} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{pp}} + \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}}. \end{aligned} \tag{2}$$

In the above equation, N_{PC} is the mean number of participants in the low density corona, which undergo single nucleon-nucleon collisions whose produced particles escape the interaction region unscathed. Since at high energy hadron production in neutron-neutron as well as in neutron-proton collisions closely resembles that in proton-proton collisions at the same beam energy, the second (approximate) equality in Eq. (2) holds true. The rapidity density in pp collisions is measured, while that in the core is assumed to be that of a completely equilibrated hadronic source.

At very high energy (typically RHIC energies) where particle rapidity distribution is wide, the second term on the right hand side of Eq. (2) can be written [7]:

$$\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}} = V \rho_0 \left\langle \frac{\mathrm{d}n_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}} \tag{3}$$

where n_i is the density of hadron species i in the fully equilibrated average fireball of freeze-out volume V and ρ_0 is the density of fireballs per unit of rapidity at mid-rapidity. For a collision of nuclei with mass numbers A and B, the volume of the core at freeze-out can be estimated:

$$V = f(V_0 - \delta V_0) \approx f \left(\frac{N_{\mathrm{P}}^A + N_{\mathrm{P}}^B}{2n_0} - \frac{N_{\mathrm{PC}}^A + N_{\mathrm{PC}}^B}{2n_0} \right) = \frac{f}{2n_0}(N_{\mathrm{P}} - N_{\mathrm{PC}}). \tag{4}$$

In Eq. (4) N_{P} is the number of participants, N_{PC} is the number of participants in the corona; $V_0 \approx N_{\mathrm{P}}/2n_0$ (n_0 being some initial density related to nuclear density) is the average of the initial overlap volume of the two colliding nuclei; $\delta V_0 \approx N_{\mathrm{PC}}/2n_0$ is the average volume of the corona, f is a "growth factor" which takes into account the expansion of the system between the initial overlap time and freeze-out. It should be stressed that the essential point here is the proportionality between the core volume and the number of participants of the core obtained as difference between the total number and that of the corona; indeed, as we will see, the knowledge of the parameters f and n_0 is not needed for our purpose.

Plugging Eq. (4) into (3) we obtain:

$$\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}} = \frac{f\rho_0}{2n_0}(N_{\mathrm{P}} - N_{\mathrm{PC}}) \left\langle \frac{\mathrm{d}n_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}}. \tag{5}$$

Since charged particle multiplicity scales linearly with the number of participants in heavy ion collisions, we are led to conclude that the factor $f\rho_0/2n_0$ in Eq. (5) is independent of N_{P}, i.e. independent of centrality, provided that $\langle \mathrm{d}n_i/\mathrm{d}y \rangle_{\mathrm{core}}$ is in turn independent of centrality. As we will see, this condition holds true because of the observed independence of freeze-out parameters on centrality.

Putting Eq. (5) into (2) and dividing both sides by $N_{\mathrm{P}} \langle \mathrm{d}n/\mathrm{d}y \rangle_{\mathrm{pp}}/2$, we obtain:

$$R_A = \frac{2 \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{AA}}}{N_{\mathrm{P}} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{pp}}} = \frac{2f\rho_0}{2n_0} \frac{\left\langle \frac{\mathrm{d}n_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}}}{\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{pp}}} \left(1 - \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} \right) + \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} = \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} + A \left(1 - \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} \right). \tag{6}$$

The factor A embodies all unknown parameters and depends linearly on particle density in the core. If this factor was independent of N_{P}, the whole centrality dependence of the R_A ratio would be given by quantity related to the geometry of the collision. Indeed, we now need to define the NN collisions which form the corona, or, in other words to define N_{PC}.
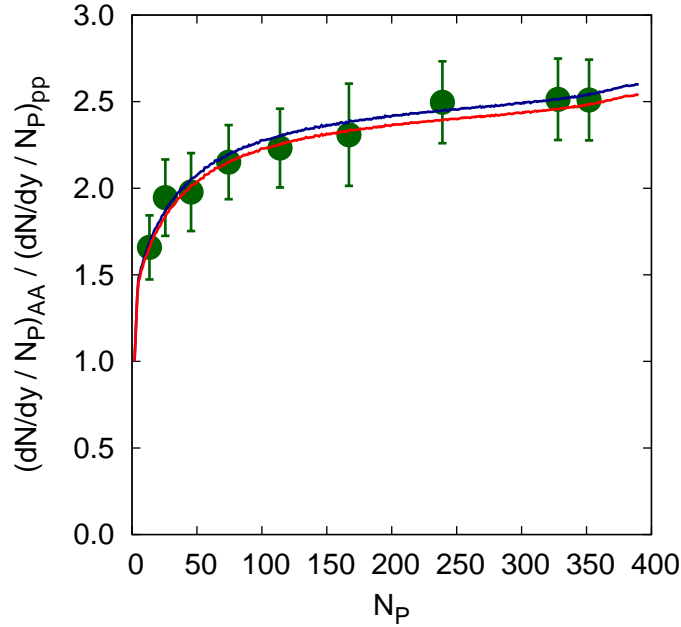
FIG. 1: Ratio R_A (see text for definition) for the ϕ meson in Au-Au collisions at $\sqrt{s}_{\mathrm{NN}} = 200$ GeV. The data points are from STAR [23] while the lines are calculated according to the Eq. (8) by fixing A in the 2nd most central and in the mid-peripheral bin.

Based on Eq. (1) for hA collisions, where the impinging and target nucleons collide only once, we choose to define N_{PC} as the number of nucleons colliding only once. Explicitly:

$$N_{\mathrm{PC}} = N_{\mathrm{S}}^A + N_{\mathrm{S}}^B \tag{7}$$

in which $N_{\mathrm{S}}^{A,B}$ are the numbers of such singly colliding nucleons from nuclei A and B respectively [1].

Armed with the definition (7) of single collisions in the corona, and with the equation (6), we are now in a position to test the model on the data by calculating N_{P} and N_{PC} with the Glauber model.

IV. DATA ANALYSIS AND RESULTS

We have emphasized that the ϕ meson provides us with an excellent probe to test models of strangeness suppression, and so does it for the core-corona model and the Eq. (6), that we rewrite here:

$$R_A = \frac{2\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{AA}}}{N_{\mathrm{P}} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{pp}}} = A + \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}}(1 - A). \tag{8}$$

Since ϕ is immune from finite size effects, i.e. canonical suppression, the factor A is independent of centrality because chemical freeze-out temperature is found to be centrality-independent. We can then fix the factor A from the data in one centrality bin and see how well the normalized yield R_A is described at other centralities by calculating N_{P} and N_{PC} with a Glauber Monte-Carlo simulation.

For our Glauber Monte-Carlo calculation we have implemented essentially the same algorithm used in ref. [24]. Our calculated number of participants in the corona according to formula (7) is shown in Fig. 2. In Fig. 1 R_A for the ϕ meson measured at RHIC at $\sqrt{s}_{NN} = 200$ GeV [23] is compared with the theoretical calculation. The two lines are

---

[1] In ref. [13] we have used a different definition of N_{PC}, i.e. twice the minimum between N_{S}^A and N_{S}^B. We find that the present definition is conceptually more satisfactory and better motivated experimentally. However, they eventually lead to very similar results.

calculated according to the Eq. (8) by fixing the factor A from two different centrality bins. We can see that in both cases the agreement between model and experiment is excellent.
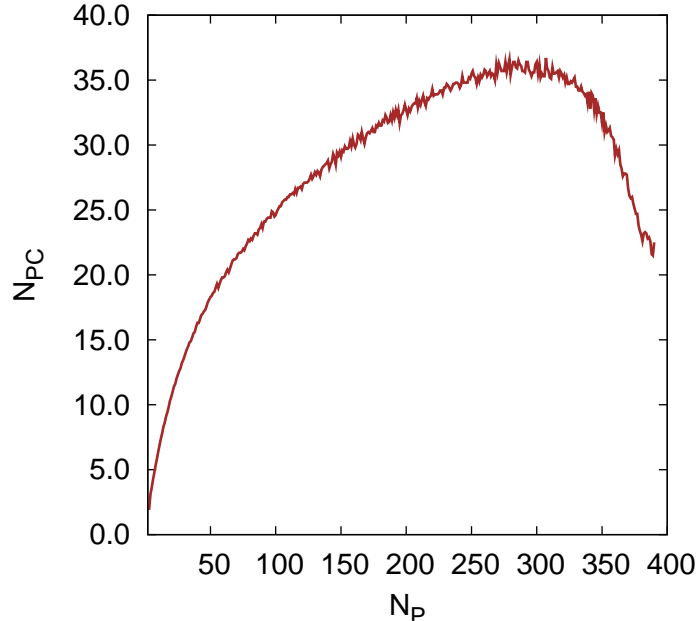

FIG. 2: Number of nucleons N_{PC} undergoing one collisions defining the corona as a function of N_{P} in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

On the left panel of Fig. 3, similar curves are shown for Λ, $\bar{\Lambda}$, $\Xi^{\pm}$ and $\Omega + \bar{\Omega}$ compared with R_A's measured at RHIC [17] at the same beam energy. The factor A is fixed to the 2nd most central bin[2] and, as expected, the model overshoots the data in the most peripheral collisions. This is because the factor A is not in fact independent of centrality and should decrease in very peripheral bins due to strangeness canonical suppression. We note in passing that the difference between the curve and the points gives then quantitative information about the volume of the average fireball at mid-rapidity.

In Fig. 4 we show the fraction of particle production from core and corona as a function of centrality for different particle species. This plot shows that the hierarchy of enhancement slopes observed at RHIC is nicely reproduced in this approach. According to Eq. (8), the higher is A, the steeper is the increase of R_A as a function of N_{P}. Since A depends on particle species through the ratio:

$$\frac{\left\langle \frac{\mathrm{d}n_i}{\mathrm{d}y} \right\rangle_{\text{core}}}{\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\text{pp}}}$$

the observed hierarchy simply reflects the hierarchy of ratios of mid-rapidity densities in heavy ion to NN collisions, therefore $\Omega > \Xi^- > \bar{\Xi}^+ > \phi > \Lambda > \bar{\Lambda}$ as it results from Fig. 4.

The model can be further tested with the RHIC data directly with the Eq. (2) in the statistical hadronization model framework (see ref. [1]). The hadron radiation from the corona part can be estimated by taking the experimental rapidity densities of different hadron species i in pp collisions [23, 26, 27] measured by the STAR collaboration and multiplying these with the number of corona participants N_{PC}. This number can be determined in a twofold way: by fitting it as a free parameter or calculating it directly from the Glauber model as the total number of singly colliding nucleons as in Eq. (7). In the first case we will have 4 free parameters that must be fitted to the measured rapidity densities at different centralities while in the second case we have 3 free parameters only. The fitted and calculated N_{PC} as a function of N_{P} at different centralities are shown in fig. 5. One can see that the fitted and calculated

---

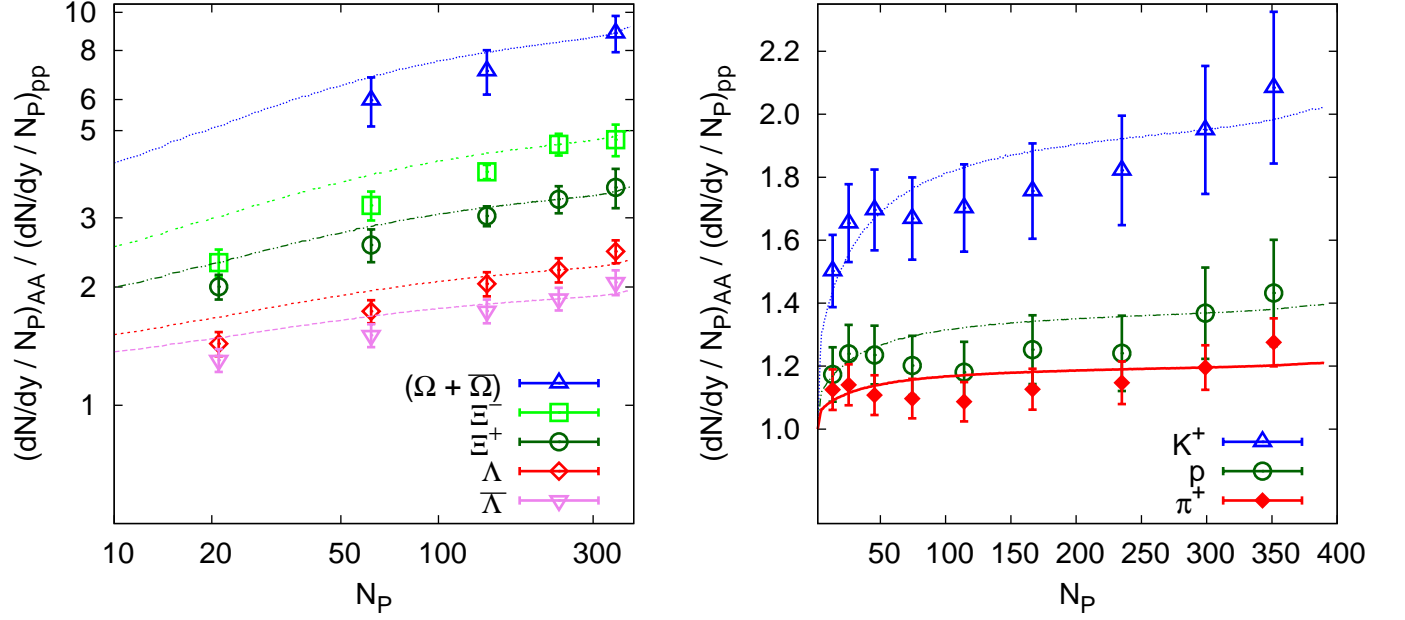[2] except $\Omega + \bar{\Omega}$ to the most central bin

FIG. 3: **LEFT**: Ratio R_A (see text for definition) for hyperons measured in Au-Au collisions at $\sqrt{s}_{\text{NN}} = 200$ GeV. The data points are from STAR [17] while the lines are calculated according to the Eq. (8) by fixing A in the most central bin.
RIGHT: The same quantity R_A for π^+, K^+ and p in Au-Au collisions at $\sqrt{s}_{\text{NN}} = 200$ GeV. The data points are from STAR [25] while the lines are calculated according to the Eq. (8) by fixing A to the 2nd most central bin.
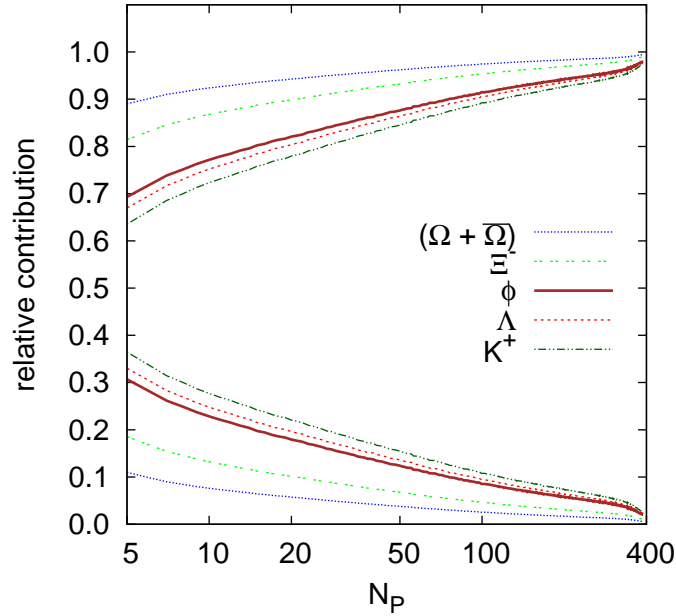

FIG. 4: Fraction of produced particles coming from core (upper lines) and corona (lower lines) as a function of centrality.

number of single collisions agree very well with each other in peripheral and semi-central collisions while in central collisions the relative emission from the corona is too small for us to reliably fit the number of single collisions. We also remark that hadron yields are described better in this two-component formalism than the conventional statistical hadronization model analysis [1] with the γ_S parameter.
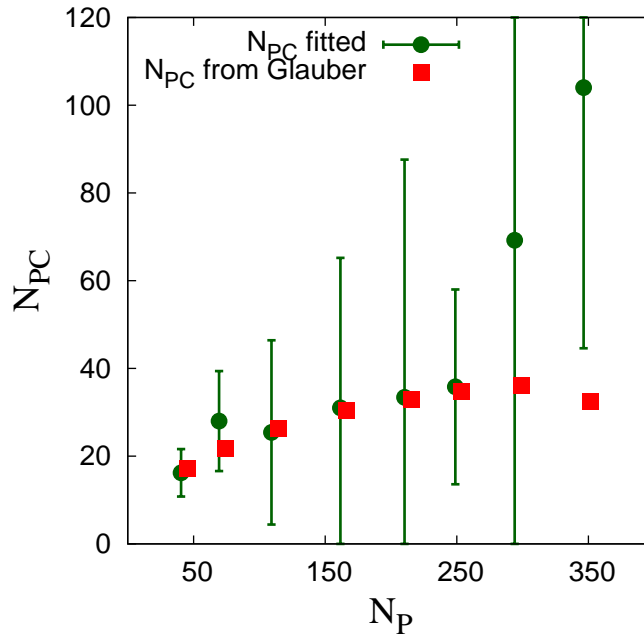
FIG. 5: Number of corona participants N_{PC} at different centralities. The square dots denote the values calculated from Glauber model while the round ones denote the values arising from fitting N_{PC} as a free parameter. The round symbols are shifted 5 units of N_P rightward for clarity.

V. SUMMARY AND CONCLUSIONS

In summary, we confirm our early finding [13] that strangeness enhancement from peripheral to central relativistic heavy ion collisions at RHIC at $\sqrt{s}_{NN} = 200$ GeV can be well described by a model where particle production arises from two sources: a fully equilibrated core at a temperature of ~ 160 MeV as in the statistical model and an outer region of single NN collisions, called corona. Since in NN collisions relative strangeness production is suppressed with respect to a fully equilibrated grand-canonical core, the observed enhancement going from peripheral to central stems from the increased weight of the core with respect to corona. The enhancement is thus mainly a geometrical effect and it is not driven by the conservation of net strangeness within small regions in the core itself (canonical suppression picture): this effect shows up only in very peripheral collisions where the whole core's volume is presumably small.

The key probe for our argument is the ϕ meson which is immune from canonical suppression and has essentially no feeding from high-lying resonances. The observed rise of relative ϕ yield as a function of centrality is an unambiguous signal that the increased production of strangeness from peripheral to central collisions is not an effect of strangeness conservation nor can it be explained by an increase of temperature, which is found to be constant throughout. The ϕ enhancement also favors the idea that corona consists of independent NN collisions rather than small clusters hadronizing in full chemical equilibrium. In the latter case, with a hadronization temperature at the same value of around 165 MeV (as confirmed by analysis of pp collisions), ϕ normalized production would be flat as a function of centrality.

The success of this description indicates, as pointed out, that a fully equilibrated core is formed at any centrality in Au-Au collisions at $\sqrt{s}_{NN} = 200$ GeV. Arguably, this should occur also at lower energies and so core-corona superposition is likely to explain strangeness enhancement observed by NA57 experiment in Pb-Pb collisions at $\sqrt{s}_{NN} = 17.3$ GeV. It becomes then crucial, in order to locate the onset of full chemical equilibrium in the core, to study the production of hyperons and chiefly ϕ mesons as a function of centrality in the energy range from few GeV's to 20 GeV. When, at some low energy or centrality, the data will start to be well reproduced by a fully equilibrated core, that might be be the point where deconfinement has occurred.

Finally, the superposition of core and corona appears to be a general feature of relativistic heavy ion collisions which should be taken into account for the analysis of all observables besides particle chemistry. This has been pointed out in refs. [9, 10] and in a very recent analysis [28]. The definition of the corona is not unique and our results indicate that it should be based on NN collisions rather than local density [9, 10, 11]. In this regard, a global fit to particle spectra [28] also favors our definition of corona as being made of those nucleons undergoing one collision.

Acknowledgments

We are greatly indebted with H. Caines and J. H. Chen from STAR collaboration for their help in handling particle production measured by STAR and useful discussions. We acknowledge stimulating and very useful discussion with P. Steinberg regarding Glauber model calculations.

References

[1] J. Manninen and F. Becattini, Phys. Rev. C **78**, 054901 (2008).

[2] J. Cleymans, B. Kampfer, M. Kaneta, S. Wheaton and N. Xu, Phys. Rev. C **71** 054901 (2005); W. Florkowski, W. Broniowski and M. Michalec, Acta Phys. Polon. B **33** (2002) 761; P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B **518** (2001) 41.

[3] J. Adams *et al.*, STAR Collaboration, Phys. Rev. Lett. **98** (2007) 062301.

[4] J. Cleymans, B. Kampfer, P. Steinberg and S. Wheaton, *Strangeness saturation: Energy and system-size dependence*, arXiv:hep-ph/0212335; J. Cleymans, B. Kampfer, M. Kaneta, S. Wheaton and N. Xu, Phys. Rev. C **71** 054901 (2005).

[5] F. Becattini, M. Gazdzicki, A. Keranen, J. Manninen and R. Stock, Phys. Rev. C **69** (2004) 024905.

[6] C. Hohne, F. Puhlhofer and R. Stock, Phys. Lett. B **640** (2006) 96.

[7] F. Becattini, J. Manninen and M. Gazdzicki, Phys. Rev. C **73** (2006) 044905.

[8] F. Becattini and U. W. Heinz, Z. Phys. C **76** (1997) 269 [Erratum-ibid. C **76** (1997) 578]; F. Becattini and G. Passaleva, Eur. Phys. J. C **23** (2002) 551.

[9] P. Bozek, Acta Phys. Polon. B **36** (2005) 3071.

[10] K. Werner, Phys. Rev. Lett. **98** (2007) 152301.

[11] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A **789**, 334 (2007).

[12] A. R. Timmins, *Strange Particle Production at RHIC*, arXiv:0810.0017.

[13] F. Becattini and J. Manninen, J. Phys. G **35** (2008) 104013.

[14] A. Baran, W. Broniowski and W. Florkowski, Acta Phys. Polon. B **35** (2004) 779.

[15] S. Hamieh, K. Redlich and A. Tounsi, Phys. Lett. B **486** (2000) 61;

[16] F. Antinori *et al.*, WA97 Collaboration, Phys. Lett. B **433** (1998) 209; F. Antinori *et al.*, NA57 Collaboration, J. Phys. G **32** (2006) 427.

[17] B. I. Abelev *et al.*, STAR Collaboration, Phys. Rev. C **77**, 044908 (2008).

[18] N. Xu, STAR Collaboration, J. Phys. G **35** (2008) 044031.

[19] B. I. Abelev *et al.*, STAR Collaboration, arXiv:0810.4979 [nucl-ex].

[20] J. Sollfrank, F. Becattini, K. Redlich and H. Satz, Nucl. Phys. A **638** (1998) 399C.

[21] J. E. Elias *et al.*, Phys. Rev. D **22** (1980) 13.

[22] B. B. Back *et al.*, PHOBOS Collaboration, Phys. Rev. C **72** (2005) 031901.

[23] B. I. Abelev *et al.*, STAR Collaboration, arXiv:0809.4737 [nucl-ex].

[24] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205.

[25] J. Adams *et al.*, STAR Collaboration, Phys. Rev. Lett. 92 (2004) 112301.

[26] J. Adams *et al.*, STAR Collaboration, Phys. Rev. Lett. **92** (2004) 112301.

[27] B. I. Abelev *et al.*, STAR Collaboration, Phys. Rev. C **75** (2007) 064901.

[28] P. Bozek, arXiv:0811.1918 [nucl-th].